Unified Aerosol Microphysics for NWP

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LONG-TERM GOALS

The long-term goal of this research is to develop a practical predictive capability for visibility and weather effects of aerosol particles over any region of the world for timely use in planning and executing DOD operations and activities. Specifically, the goal is to develop a COAMPS that is capable of simulating the full range of interactions between aerosol particles, clouds, and radiative transfer while remaining flexible, extensible and operationally practical. This new version of COAMPS is now the only operational model with data assimilation capable of studying the complex interactions between clouds, aerosol particles, radiative transfer and dynamics. The fundamental predicted variables are the concentrations of those aerosol species that are responsible for degradation of Electro-Optical (EO) propagation or that modify cloud behavior and lifetime.

OBJECTIVES

The primary objectives for this project are to design, implement, and demonstrate a flexible and extensible mechanism into COAMPS that allows new scalar variables to be added and accessed with less effort, thus enabling new development of more complex cloud-aerosol interactions. The work on this project has been divided into three phases: an investigation phase in the first year, an implementation phase in the second year, and a demonstration phase in the third year.

Another objective is the development of an aerosol microphysics library and emission inventories for use by COAMPS, NAAPS and other models. The final objective is a version of COAMPS configured to forecast the major aerosol species, yet suitable for operational use. The proposed capabilities will provide numerous opportunities to study and solve problems of interest to the Navy and DOD, as well as the climate community.

APPROACH

Upgrading scalar variable handling is a major change to a model's infrastructure, so our approach in the first year was to focus on investigating the requirements and evaluating a number of software designs. We reviewed the current implementation and existing codebase that was developed over a long period of time in an ad-hoc fashion by different researchers. We decided the best approach was to add a meta-data registry to centrally manage scalar variable properties that are user-modifiable at runtime via ASCII file and accessed with a simple, flexible, extensible application programming interface (API).

We found that scalar variables are processed from two perspectives: it may be treated as a generic variable such as when it is processed by advection, or it may be used specifically like dust in ice nucleation. The primary difficulty in adding new scalar variables is the number of locations in the software that must be modified. Since much of this editing is for general processing, it was decided to implement a mechanism where this type of generic processing could be automated. We knew that associating properties to variables would be useful to support generalized or property-driven processing so we decided that the best approach was to add a meta-data registry to centrally manage scalar variable properties that are user-modifiable at runtime via an ASCII file and accessed with a simple, flexible, extensible API. These properties are initialized at runtime and may be modified by a user through an ASCII file without rebuilding and/or recompiling the model's software. We wrap a looping mechanism around processing steps that automatically submits variables for processing based on properties set by the user. We tested three different approaches with an evaluation at the end of each approach before coming to a design decision for the implementation.

We also chose to reject certain approaches that are overly complex. We decided against a software approach that generates the code because of the expertise required to maintain and extend this approach. WRF uses this technique and it provides certain benefits like reducing the time spent testing variable existence at runtime. At NRL, our scientists are experienced in NWP programming but have little support from professional software engineers. These researchers have years of experience with our models and any new approach that requires them to unnecessarily recode the model would be counterproductive. Because our models are used operationally, DoD IA requirements discourage software that generates code that may be unknown to the user.

Our approach for the actual code development in the second year was to retain the aerosol variables in a separate module which allows us to test property-driven processing on the aerosol variables first before migrating this technique into the main body of COAMPS. This approach allowed us to correct complex problems such as the use of an inconsistent temporal integration scheme for the aerosol scalars. Throughout the development, the software changes were first tested against the previous implementation and found to produce the same numerical results.

The approach for the third year has been to demonstrate the new model on physically relevant cases. Our approach to testing the new model for robustness, accuracy and practicality is running it day-to-day in near-operational fashion.

Lastly, our approach for the library has been to seek global, yet high-resolution, emissions inventories for use in both COAMPS and NAVGEM. Towards this goal, NRL previously developed the world's only real-time smoke emission system (FLAMBE) which has sub-kilometer resolution. NRL has also developed the only high-resolution dust source database (DSD) for SW Asia and E Asia. In this project it has been extended to cover the rest of the world's deserts. The development of similar high-resolution emissions inventories for anthropogenic species at global scales has also been addressed.

WORK COMPLETED

We have completed the coding changes required to implement the new approach to scalar forecasting in COAMPS. These changes were far-reaching and required careful and systematic verification of the new forecasts against those from the original code at each step. The scalar code was exercised for several physically meaningful cases to further demonstrate that the upgrade was successful (see next section.) The final step is to merge the scalar version of the code with the main 'trunk' of the COAMPS model. This will be done as soon as the tropical cyclone version of COAMPS is merged with the main trunk of COAMPS.

The first application was cycling the model for dust events in SW Asia. However, the weather systems were too dry to allow us to test the aerosol-cloud interactions. We shifted instead to a winter-time passage of a low pressure system across North Africa and the Mediterranean Sea (Figure 1). The strong southerly winds ahead (east) of the low produced great amounts of dust which were mixed throughout the lower troposphere and lifted to the mid-troposphere where high humidities were achieved and clouds formed. Our approach to demonstrating the multi-species capability was to include both dust and smoke in COAMPS and extend the domain of the Mediterranean low case study southward to include the smoke production regions of the Sahel where seasonal fires numbering in the thousands were occurring.

The development of the NRL 1 km high-resolution DSD continued with mapping and identifying discrete (1-10s km) dust sources in N Africa, S Africa, the United States, S America, and Australia. In addition to using the technique of precisely locating dust point sources by analyzing the NRL DEP and DEBRA satellite products we extended our approach by including machine learning. Using MODIS multispectral albedo data, MODIS land surface data, and the NRL DSD for SW Asia and E Asia a multi-variate, non-linear classification was performed by a Self-Organizing Map (SOM) Neural Network. The product of the SOM is a set of maps where land surfaces that have distinct physical characteristics and a distinct reflectance signature are grouped into 1,000 classes. Only a small subset of these classes corresponds to sediment rich, dust producing land surfaces such as dry lake beds, ephemeral streams, fallow farm fields, and desertifed lands. The addition of the SOM technique to our approach has eliminated a large fraction of time spent on hand analysis and digital entry of dust sources into the database. Tuning of the subset is necessary. There are instances where classes accurately map dust sources for one region of a country, but also incorrectly map a small fraction of land that is non-dust producing. There are also some instances where dust sources are not mapped due to the choice of MODIS land surface types. Figure 2 shows dust plumes (seen in fuchsia) emanating from the Bodele Depression, Chad, North Africa. The inset images show the 1,000 SOM classes found and the selected subset of SOM classes that map dust producing land surfaces. Figure 3 provides another example of high-resolution dust source identification using SOM classes for the American Southwest.

RESULTS

To evaluate the new handling of aerosol particles and their interaction with COAMPS microphysics, a pseudo-operational test case was developed covering North Africa. This case was used to validate handling of feedback between nests and interactions between dust production, cloud nucleation, and dust scavenging. The dust serves as a source of cloud droplet nuclei in the COAMPS two-moment cloud microphysics scheme. The dust and cloud microphysical processes are fully interactive in that the cloud droplet nucleation acts as a sink on the dust concentration in regions of supersaturation and as a source of dust in regions where droplet evaporation is occurring. Auto-conversion from cloud water to rain water in the two-moment cloud scheme also acts as a sink on the dust concentration through the precipitation process. The only process not tested was direct radiative heating by the dust.

The case study is a winter-time passage of a low across North Africa and the Mediterranean Sea (Figure 1). The strong southerly winds ahead of the low exceed the threshold for dust mobilization and great amounts of dust are lifted and mixed throughout the lower troposphere causing widespread low-visibility conditions. The comparisons with surface and satellite data show that COAMPS has captured this event. The dust plume is accurately aligned with the observed dust event. COAMPS forecasts the heavy dust loading over Algeria, Tunisia and the Mediterranean Sea. Synoptic scale motions lift the dust to the mid troposphere as it streams northward. The upward transport of the dust eventually leads to saturation conditions. The dust is included in the cirrus nucleation parameterization in COAMPS and thus the clouds are modified by the presence of dust. Conversely the precipitation scavenges the sub-cloud dust and removes it from the system. Few observations are available for quantitative validation of the aerosol implementation but the model sensitivity studies clearly showed that these mechanisms are correctly operating. In some locations, more ice was produced at warmer temperatures due to the dust-enhanced nucleation. The increase in the number of ice crystals occurred at elevations where the ice multiplication process is important, thus further amplifying the impact of dust on cloud-aerosol interactions and producing regions of enhanced precipitation.

IMPACT/APPLICATIONS

Climate studies have suggested the importance of interactions between aerosol particles, clouds, and radiative transfer via the processes known as the direct effect (changes in radiative transfer), semi-direct effect (changes in boundary layer dynamics), and indirect effect (changes in the cloud life cycle). Since climate is made up of many weather events, these same processes should be important to NWP. However, the case for fully interactive aerosol particles in operational NWP models has not been made. The climate metric of radiative forcing is not meaningful to NWP since extensive spatial and temporal averaging is invoked and the local impact is hidden. Regional impacts have been largely demonstrated with model sensitivity studies and anecdotal evidence. The interactive COAMPS model will allow a quantitative assessment of the significance of aerosol particles to NWP.

An alternate impact on NWP lies in the aerosol direct effects on remote sensing, data assimilation and validation. Aerosol particles can cause biases in satellite-sensed radiances at the top-of-the-atmosphere, errors in sea surface and other ocean and surface retrievals, and errors in forward modeling of observed quantities. An interactive COAMPS model will allow the study of these effects and the development of mitigation strategies.

TRANSITIONS

The Fleet Numerical Meteorology and Oceanography Center (FNMOC) operational models use the USGS database for dust source allocation in all regional domains except SW Asia. Two COAMPS case studies are in progress to compare the NRL 1 km DSD against the United States Geological Survey's (USGS) land surface database. The first case study will investigate spring time dust events during 2010 in East Asia. The second case study will examine cloud/dust/smoke interactions during the spring of 2013 in N Africa. The validation test reports (VTRs) in FY14 for these case studies will provide statistics on dust storm false alarm rate, clear sky conditions, and total skill for visibilities that are verified against airport surface observations and METARS along with statistical comparisons of forecasted aerosol optical depth (AOD) and AErosol RObotic NETwork (AERONET) ground-based AOD data.

Testing and validation of the new scalar version of COAMPS will be reported in a VTR in FY14 in the 6.4 Small-Scale Atmospheric Models project. Upon completion of the VTR, the new version will be transitioned to COAMPS-OS and be available for alpha and beta testing by FNMOC.

RELATED PROJECTS

ONR 6.2 “Application of Earth Sciences Products” supports improvements in aerosol microphysics and model initialization. The implementation of COAMPS at FNMOC is supported by 6.4 funding from PMW-120 for “Small-scale Atmospheric Models”. This funding also supports development and generation of products for use by the fleet. The NRL 6.1 Accelerated Research Initiative “Physics of Cloud Variability” helps understand atmospheric aerosol interactions.

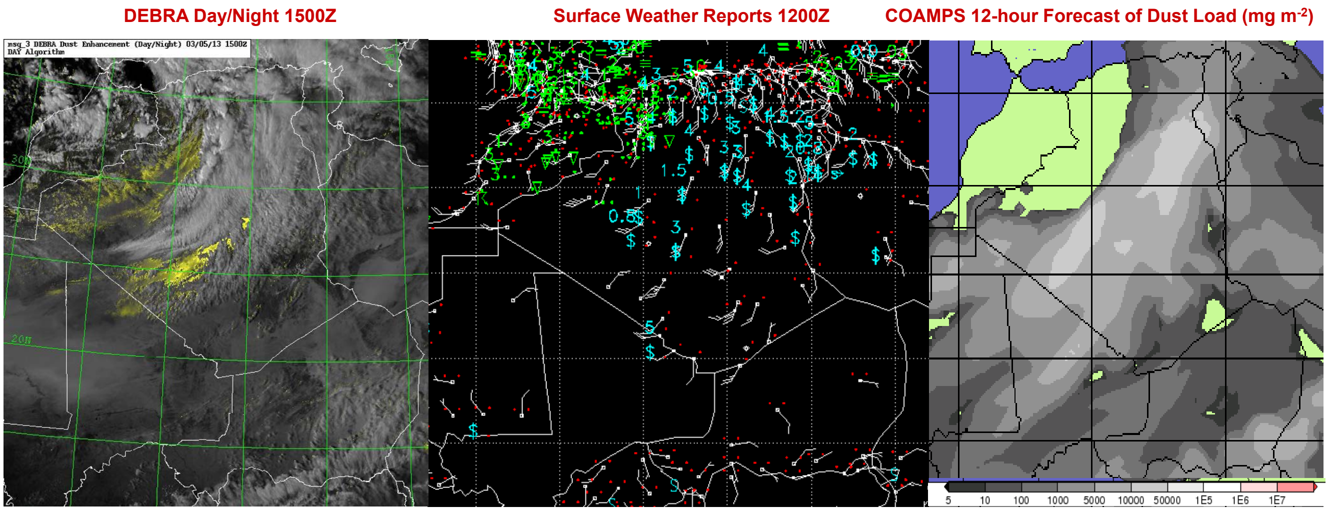

Figure 1: Comparison of observations during an Algerian dust storm with the 12-hour forecast from COAMPS, valid at 12GMT March 3, 2013. Left: MSG visible image (black and white shades) with the DEBRA dust enhancement product (yellow shades) showing heavy dust at low levels below cloud shield. Middle: surface weather observations of visibility (blue numbers, km) winds (barbs) and current weather showing widespread low-visibility conditions occurring in strong southerly and southwesterly winds ahead of a low pressure center. Right: COAMPS 12-h forecast of vertical mass load of dust (mg m^{-2}) accurately aligned with the observed dust event. COAMPS accurately forecasts the heavy dust loading over Algeria, Tunisia and the Mediterranean Sea.

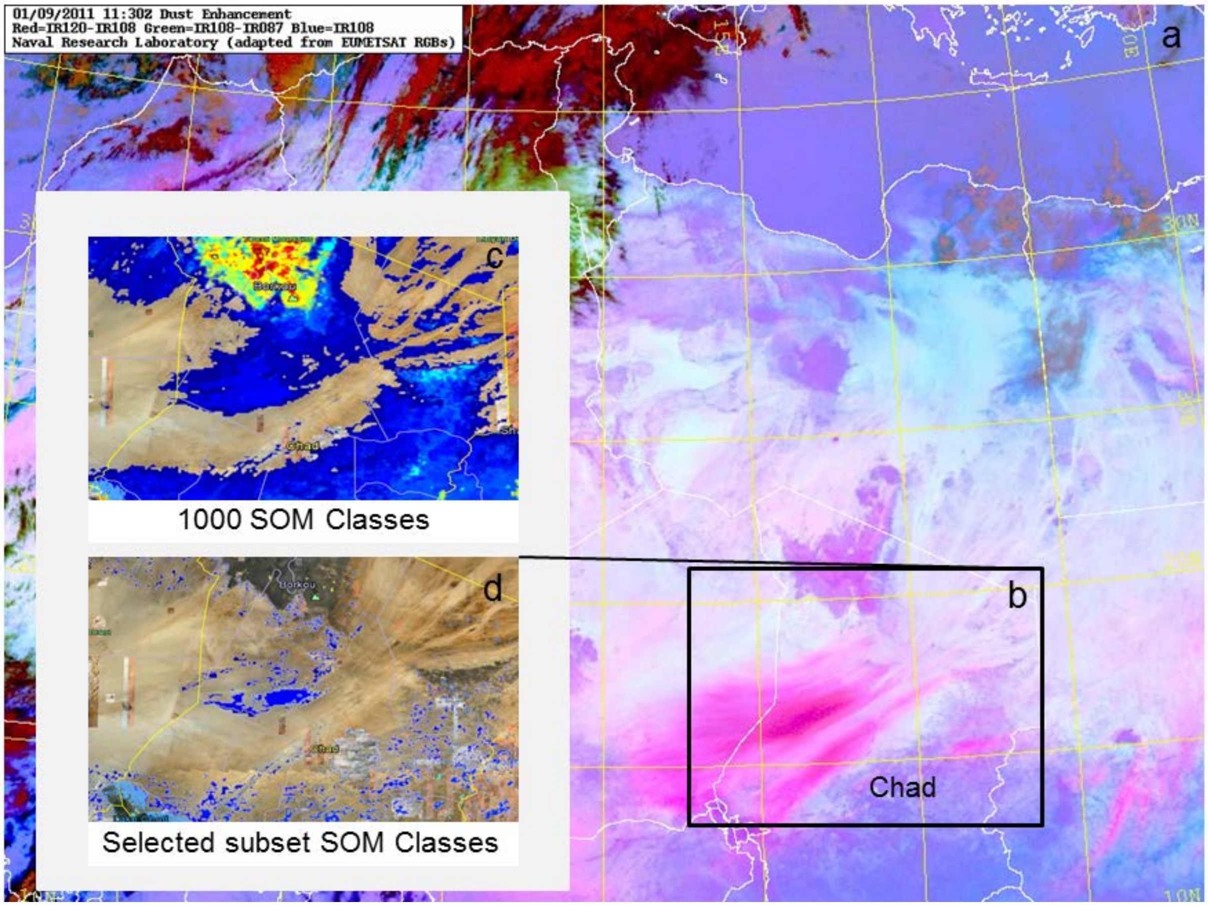

Figure 2: a) NRL Meteosat Second Generation Red Green Blue dust enhancement product for 20110109 1130Z. b) Dust plumes and clouds are seen in fuchsia emanating from the Bodele Depression, Chad, North Africa. c) 1,000 SOM classes found using machine learning technique. SOM classes vary in color from dark blue to dark red. d) Selected subset of SOM classes that correspond to dust producing land surfaces. Both c) and d) show SOM classes mapped in Google Earth.

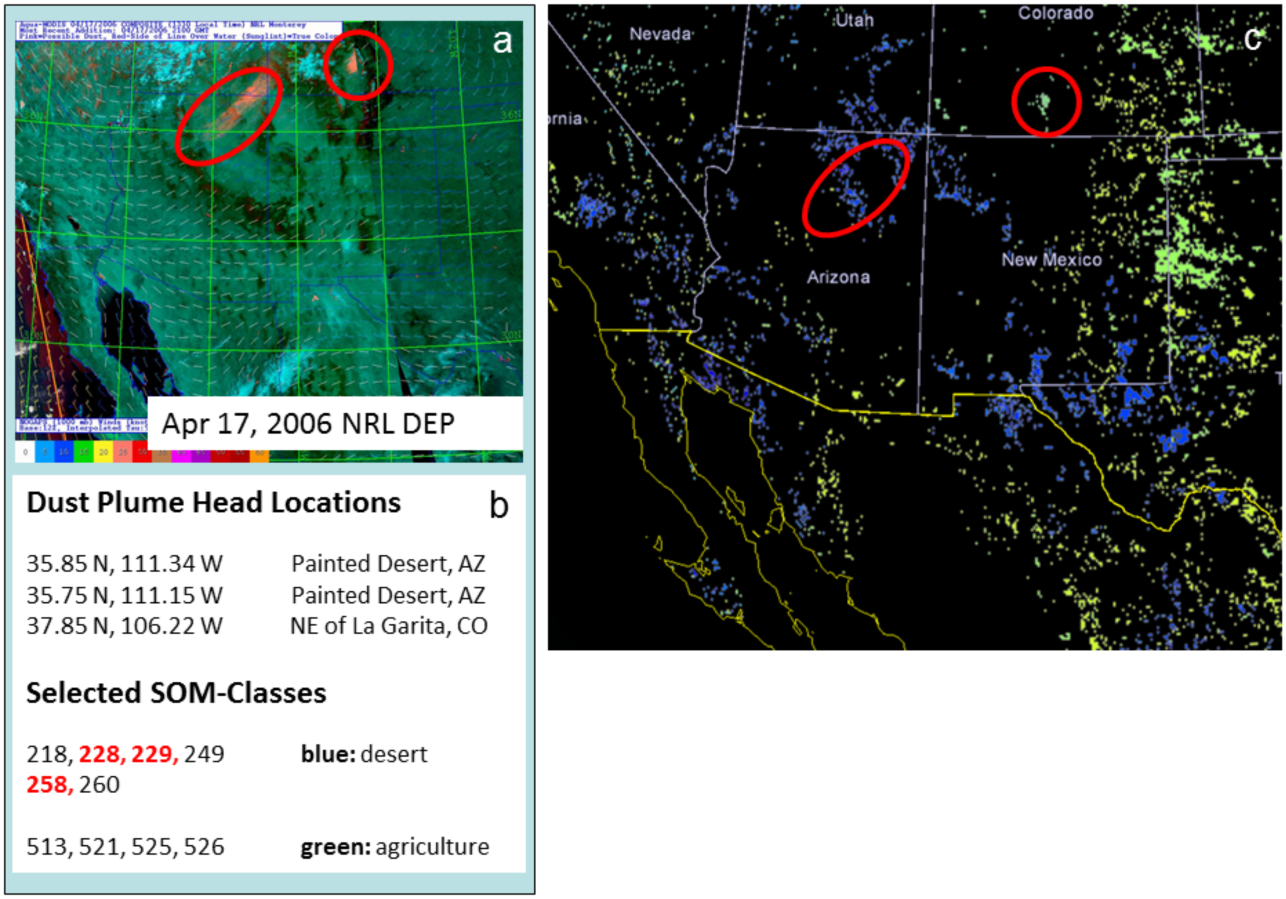

Figure 3: a) NRL Dust Enhancement Product (DEP) for 20060417 21Z. The red oval shows dust plumes arising from sources in the Painted Desert, AZ. The red circle shows dust plumes in Colorado's San Luis Valley. b) Dust plume latitude and longitude location is give. Six of the 1,000 SOM classes and five of the 1,000 SOM classes map the dust sources found in the Painted Desert and the San Luis Valley, respectively. c) Selected subset of 1,000 classes that map dust sources in the American Southwest. Blue areas correspond to classes associated with desert regions. Green areas are SOM classes associated with agricultural land.